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LABORATORY TESTS OF HIGH TENSILE BOLTED STRUCTURAL JOINTS

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STRUCTURAL DIVISION

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EXPLANATORY STATEMENT

Practices in the design of riveted and bolted joints have developed largely from experience and have not always been supported by conclusive experimental data. With this fact in mind, twelve sponsoring organizations instituted the Research Council on Riveted and Bolted Structural Joints, in 1947.

Important among the projects of the Research Council is the study of high-strength bolts in structural joints. The high-strength bolt is a comparatively new type of structural fastener, and its use combines the field economies of bolts with strength greater than that of rivets.

At the Centennial Convention of the ASCE at Chicago, Ill., in 1952, a group of papers were presented describing research that had been done in the field of structural joints, with particular emphasis on study of the high-strength bolt.

These papers are currently being published as Proceedings-Separates and will be distributed over a period of several months beginning in May, 1954. Later, they will be gathered to form a single symposium in the Transactions of the ASCE. The six papers in this group are as follows:

"The Work of the Research Council on Riveted and Bolted Joints," by W. C. Stewart;

"Laboratory Tests of High-Tensile Bolted Structural Joints," by W. H. Munse, J. M. ASCE, D. T. Wright, and N. M. Newmark, M. ASCE;

"Comparative Behavior of Bolted and Riveted Joints," by Frank Baron, M. ASCE, and Edward W. Larson, Jr., J. M. ASCE;

"Slip Under Static Loads of Joints With High-Tensile Bolts," by R. A. Hechtman, A. M. ASCE, D. R. Young, and A. G. Chin and E. R. Savikko, Junior Members, ASCE;

"Fatigue in Riveted and Bolted Single-Lap Joints," by J. W. Carter and K. H. Lenzen, Associate Members, ASCE, and L. T. Wyly, M. ASCE;

"Structural Application of High-Strength Bolts," by T. R. Higgins and E. J. Ruble, Members, ASCE."

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LABORATORY TESTS OF HIGH TENSILE BOLTED STRUCTURAL JOINTS

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SYNOPSIS

This paper summarizes the results of a number of static and fatigue tests conducted at the University of Illinois on structural joints using high tensile steel bolts as the fasteners. The tests indicate that high tensile bolted joints are generally superior to similar riveted joints, whether subjected to static or fatigue type loadings.

INTRODUCTION

The use of bolts is certainly not new to steel construction. Bolts are used in the erection of structures and in some instances have served as the permanent fasteners, although this latter type of application is often restricted by local codes and specifications for steel construction. Another factor which has limited previous use of bolts in structural joints has been the feeling among engineers that the nuts on the bolts might become loose, thereby endangering the structure. However, the results of recent field and laboratory studies indicate that there is no danger in the use of bolts even under extreme conditions, providing they are high tensile bolts and that they are installed in the proper manner. In fact most of the studies have shown that the high tensile bolted joints are superior to similar riveted joints.

In order to assemble a bolted joint, it is necessary that the bolts be somewhat smaller than the bolt holes. However, since bolts do not expand and fill the holes, it is essential that the bolts be drawn up extremely tight to protect the joint against slipping. This, then, means that the load is transferred across the joint by the friction between the connected parts rather than through shear on the fasteners, except for the case of very high static loads.

It has long been known that the frictional forces in a riveted joint, produced by the clamping action of the rivets, determine the ability of the joint to resist slip at working loads. Nevertheless, the design of riveted joints is invariably based on the premise that the load is transferred from one member to another by means of direct shear on the rivets. By using high tensile bolts as fasteners one may obtain very large clamping forces. This makes it possible to design bolted joints in which the entire working load is carried by means of friction.

One of the first studies on the use of high bolt tensions for structural joints was presented by Professor W. M. Wilson (1)[4] in some of his early work on structural fatigue. This work, reported in 1938, was one of the factors which

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led to the program of tests reported herein. The present tests were planned to determine both the static and fatigue strength of structural joints fabricated with high tensile bolts. Numerous individual studies have been made to determine the general characteristics of the joints under a variety of conditions.

The bolts, because of their importance in this problem, have been studied by themselves as well as in the joints. Calibration tests, tensile tests and torque tests have all been conducted on the bolts in order to furnish information that will permit their use to greatest advantage.

Tests of Bolts

The magnitude of the axial bolt tension and the ability of the bolt to maintain this tension are of primary importance in the proper functioning of bolted structural joints. In the laboratory, this axial tension has been determined with extensometers which are used to measure the change in length of the bolts as they are tightened. This procedure would be out of question for field use; however, in the laboratory it provides a simple means by which the bolt tensions may be carefully controlled.

(a) Bolt Material: The bolts used in this study were to be of the type furnished under ASTM Designation A325-49T, "Quenched and Tempered Steel Bolts and Studs". This provides for medium carbon (0.30 % minimum) quenched and tempered steel bolts having a yield strength of about 80,000 psi and a tensile strength of about 110,000 psi. It is not necessary that they be alloy steel bolts.

Upon close analysis it was found that the 3/4-in. bolts furnished for this work did not quite meet this specification. Not only were the ultimate strengths of the 3/4-in. bolts a little lower than required but the size of the bolt head was slightly less than that specified. The mechanical properties of the bolt materials as determined from tests of 0.505-in. diameter coupon specimens cut from each bolt size are given in Table 1. The ultimate strengths of the test bolts are presented in Table 2. This tabulation indicates that the 3/4-in. bolts were not quite as strong as required by the specification.

(b) Load-elongation Tests: For proper use of the bolts in the laboratory tests, it was necessary to obtain their load-elongation characteristics. This was accomplished by applying a tensile load to the bolts with a testing machine and by measuring simultaneously the change in length of the bolt with an extensometer. It is evident that the load-elongation characteristics for the bolts will vary with the grip and diameter of the bolts. Therefore these factors must be considered in any calibration tests.

For maximum efficiency in bolted structural joints it would be desirable to have the total elongation in the bolts, for a given grip and axial bolt-tension, as high as possible. Consequently, several studies were made in which the bolt elongation, for a given axial tension, was increased by reducing the effective area of the bolt shank. This was accomplished by simply undercutting or fully threading the shank of the bolt.

The results of the load-elongation tests on 1-in. bolts with various shank conditions are presented in Fig. 1. It is apparent that the reduction in shank increased the elongation of a bolt for a given load but decreased its ultimate capacity and elastic limit. The first of these effects is desirable whereas the others are not.

Based on the calibrations of the bolts with a plain shank the effect of threading or undercutting the shank is indicated by the following tabulation:

Shank Condition (1-in. bolt)	Increase in Elongation (in per cent)	Decrease in Ultimate Capacity (in per cent)
Fully threaded	20	7
Reduced to 7/8 in.	11	9
Reduced to 13/16 in.	25	20
Reduced to 3/4 in.	53	32

It can be seen readily that to thread fully the bolt shank gave the largest ratio of increased elongation to loss of capacity. However, the 20 per cent increase in elastic elongation may not be worth the added cost of threading the full shank of the bolt.

Another type of calibration test conducted was that in which the bolt-nut assembly was lubricated. This procedure reduced the torque necessary to obtain a given axial tension in the bolt, but had no effect on the load-elongation characteristics.

(c) Load Torque Tests: A number of studies were made to determine the relation between the torque applied to tighten a bolt and the axial tension in the bolt produced by this torque. These studies were made for a number of different grips and bolt diameters.

In several previous investigations (3, 11) it has been demonstrated that the load-torque relationship for bolts such as those used in this investigation may best be expressed by a formula of the type:

$$T = K D P \tag{1}$$

where

T = torque in in. lb.
K = torque coefficient, dimensionless.
D = nominal bolt diameter in in.
P = bolt tension in lb.

The torque coefficient K in equation (1) may be expected to vary somewhat with the material and the condition of the surfaces of the bolts, nuts and washers. However, a fair approximation to the torque may be obtained by the use of a value of K of 0.20.

Table 3 presents a summary of the values of torque coefficient obtained in tests of bolts of three diameters and of two grips. In this case, the average torque coefficient was found to be 0.221 with a probable error of ± 0.016. It might also be noted that there was considerable variation in the magnitude of the coefficient from test to test. This might be expected, however, since the bolts were all tested in the as-received condition.

Lubrication of the sliding surfaces of the bolt-nut assembly (lubricated with No-Oxid)[5] lowered the coefficient of friction and, accordingly, the value of the torque coefficient. When the bolt and nut or the nut alone were treated a torque coefficient of 0.15 was obtained, whereas when the bolt alone was treated a torque coefficient of 0.184 was obtained. From these results it is apparent that treating the nut alone is the more economical and effective means of reducing the torque required to produce a given axial tension in the bolt-nut assembly.

[5]No-Oxid is a special wax coating which was applied commercially.

Static Tests

In the static tests reported in this paper, a number of factors and their effect on the static strength and load-slip relationships have been studied. These variables include, (a) the ratio of nominal fastener shear to plate tension (shear-tension ratio), (b) the type of joint (riveted or bolted), (c) the bolt tension, and (d) the condition of the faying surfaces.

Description of Specimens and Tests

The specimens tested in this study were of three general types; two-fastener lap joints, three-fastener lap joints and two-fastener butt type joints. The details and dimensions of the specimens of these three groups are presented in Fig. 2 and Table 4.

The specimens of the first group were lap joints connected by two fasteners in line with the direction of load application. The second group of specimens were similar to the first group except that there were three fasteners in line instead of two. The addition of this extra fastener, however, made it necessary to increase the width of the specimen in order that the tension-shear-bearing ratios be maintained constant. The third group of specimens consisted of three series of double-strap butt-type joints connected with two fasteners in line. These specimens provided joints in which the fasteners were subjected to double shear rather than single shear.

One of the principal characteristics studied was the relationship between load and slip. The slip of the joints (relative movement between the plates) was measured at successively increasing loads by means of a pair of mechanical dial gages mounted on opposite edges of the specimens. This type of measurement does not give an exact measure of the slip at the fasteners in the joint but does give a relative measure which can be used to compare similar specimens and to give a general indication of the action of the joints.

Results of Tests

The results of the static tests of bolted joints are presented in Tables 5, 6 and 7. These tables give the maximum load carried by the joints, and the tensile, shear and bearing stresses corresponding to this load. Column 5 of the tables indicates, by the letter symbols S, T and ET, whether the joint failed in the fasteners (shear), in the plate by tearing across the net section (tension), or in the plate by tearing out the ends (end-tearing), respectively.

(a) Shear-tension Ratio: There were no bolt shear failures in the twelve tests of joints with a shear-tension ratio of 0.75; one shear failure was obtained in the twelve tests of bolted joints with a shear-tension ratio of 1.0, and 10 shear failures were obtained in the 16 tests of joints with a shear-tension ratio of 1.25. On the basis of these results, the critical shear-tension ratio of is between 1.0 and 1.25; for the lap type joints it appears to be about 1.25 whereas the value might be somewhat less than 1.25 for the butt type joints. Consequently, it would appear that the present specified shear-tension ratio of 0.75 is very conservative for high tensile bolted joints of the type tested in this study.

It should be noted also that an increase in the shear-tension ratio for high tensile bolted joints must be accompanied by an increase in the specified safe end distance. However, for the riveted joints the end distance as covered by present specification was found to be entirely adequate, as indicated by the results given in Table 8.

(b) Type of Joint: A comparison of the two-fastener lap joints, three-fastener lap joints and two-fastener butt joints indicates that the joint type had less effect on the strength of the joints than did the variation in the steel plate used in the various specimens. The specimens of Series S-7, S-8 and S-9 were fabricated on one date, the other specimens on another. A comparison of the ultimate tensile strengths indicates that there was a greater difference in the values for the two-fastener lap joints than there was for the various types of joint, although the variation in strength for the two-bolt joints was not large.

Considering only the joints fabricated from the second set of plates (Series S-10 through S-17) one finds that the two-fastener lap joints were slightly stronger than the three-fastener lap joints and the two-fastener butt joints. These differences, apparently due to variation in joint type, were consistent but not very large; the maximum difference never exceeded 7 per cent.

The greater strength of the two-bolt lap joint might be accounted for by the direction of loading and the shape assumed by the test specimen during testing. Because of the eccentricity of load on the lap joints, they deformed into a flattened S-shape during testing. The effect of this deformation is to rotate the direction of principal stress with respect to the original axis of the joint. As a result, the areas resisting the principal stress are slightly greater than the nominal area of the section. An examination of the bolts from those joints which failed in shear illustrates clearly this effect. The bolt fractures obtained in the lap joints were at a slight angle with the axis of the bolt whereas the bolt fractures from the butt joints were at right angles to the bolt axis.

(c) Bolt Tension: All of the tests reported in Tables 5, 6 and 7 were conducted with the bolts tightened either finger tight or to an axial tension of 35,000 lb in each 7/8 in. bolt. A comparison of these various specimens shows that the variation in bolt tension as well as the surface condition and shear-tension ratio had no significant effect on the ultimate strength of the joints.

In general, it would be expected that the bolt tension would have little effect, if any, upon the ultimate strength of the joints because the plates slip into bearing on the bolts well before the ultimate load is reached. This explains also the fact that the contact-surface preparation had little or no effect on the ultimate strengths of the joints.

(d) Surface Preparation: As previously noted, the surface preparation had little or no effect on the ultimate strength of the bolted joints. This same condition was found to exist for the riveted joints also. However, it might be noted that although the surface condition and bolt tension had little effect on the ultimate strengths of the joints, these factors had an important effect upon the load-slip characteristics of the specimens.

(e) Load-slip Characteristics: One of the principal characteristics studied in this program was the load-slip relationship. It was found that the condition of the contact surfaces, and the fastener type and its tension, had a considerable and important effect upon the load-slip relationships, whereas the type of joint (lap or butt) and the ratio of the shear to tensile stresses had little if any effect on this relationship.

An example of the type of load-slip relationships obtained in these tests is presented in Fig. 13. In this figure Specimens 1 and 4 were bolted joints with a zero tension, Specimens 2 and 5 were bolted joints with a bolt tension of 35,000 lb, and Specimens 3 and 6 were riveted joints.

With the bolts finger tight, a slip sufficient to bring the bolts into bearing occurred at a very low load. With the bolts tightened to 35,000 lb tension the joints carried an appreciable load with little or no slip, by means of friction alone. When this frictional resistance was overcome, the joints slipped markedly with only a slight increase in load until the bolts were in bearing. From this point on, the load-slip curves for the joints with zero or 35,000 lb bolt tension were quite similar.

A comparison of the load-slip curves for the riveted and bolted joints indicates that after the bolts once started to slip the riveted joints carried a considerably greater load for a given slip than did the bolted joints. However, after the rivets began to deform plastically the joint deformation increased rapidly and soon became very close to that of the bolted joint. Beyond this point, because of the greater shearing strength of the bolts, the slips for the bolted joints were generally less than those of the riveted joints.

Fatigue Tests

The second type of loading included in this program consisted of a fatigue loading in which the load was varied systematically during the test. In these studies both the bolts and the plates were considered

The use of high tensile strength bolts is based on the premise that the tension in the bolts is sufficient to transfer the forces between the members by friction and to keep the nuts from loosening. This being true, there will be little or no slip between the plates of a joint if the joint functions properly. Consequently the shear or bearing or bending in the bolts will be negligible. Small variations in bolt stress may arise from the Poisson's ratio effect; however, this variation will not be very large. As a result, it was believed that there was little likelihood of failure in the bolts of a high tensile strength bolted structural joint when subjected to fatigue type loadings. In addition, because the high clamping force of the bolts tends to distribute the load over a relatively large area and since there is no bearing of the fastener in the bolt holes, there was cause to believe that the fatigue strength of the plates of the bolted structural joints might be greater than that of the riveted joints.

Description of Tests

Most of the fatigue tests reported herein were conducted in the 200,000 lb fatigue testing machines at the University of Illinois. These machines, shown in Fig. 4, are capable of testing large structural components. A few of the smaller lap joints were tested in the 50,000 lb fatigue machines at the University of Illinois. These machines are similar in principle to the 200,000 lb machines.

The specimens were generally assembled before they were placed in the fatigue machines. After the specimens were placed in the machines, the bolts were tightened to the desired tensions using calibrated torque wrenches and elongation gages. Dial gages were then mounted on opposite edges of the specimen to obtain the relative movement between the plates of the joint. A typical joint complete with slip measuring dials is shown in Fig. 5.

During one of the reversed load fatigue tests a study was made to determine the amount of eccentricity in the joint. Strain gages (see Fig. 5) were mounted on the edges and surfaces of the center plate of the joint. From this study it was found that the eccentricity of the load in the direction of the plate thickness was approximately 0.01 in., and in the plane of the plate was only 0.1 in. In view of the size of the specimen, the size of the machine and the magnitude of the load ($\pm$70,000 lb), this eccentricity was considered to be relatively small and insignificant.

Fatigue Strength of Bolts

One of the first questions considered in this program was the fatigue strength of the high tensile strength steel bolts. It was believed that the most severe condition of loading on the bolts would occur with the joints subjected to a reversed load stress cycle. The plates of the first exploratory test specimens, therefore, were made extra heavy in order that the load on the joints might be large without producing failure in the plates. Details of the first specimens tested are shown in the upper part of Fig. 6.

In order to put high loads on the bolts it was found necessary to reduce the number of bolts to three as shown in the lower portion of Fig. 6. The circular notches shown in the center plate were made to facilitate the measurement of the bolt elongation for the center bolt.

The results of the tests which were made to study the fatigue strength of the bolts in butt-type joints are presented in Table 9. The first specimens tested were those of Series X. These specimens were tested under a constant stress cycle throughout the test and at a nominal shearing stress as high as $\pm$27,000 psi on the nominal area of the bolts for a total of 3,654,200 cycles without failure.

From the few specimens tested in the X-series it was evident that, for a shearing stress as great as $\pm$27,000 psi, there would be no failures of the bolts providing the joint did not slip. It was observed in these tests that the frictional resistance of the joints seemed to increase during the test in spite of the fact that there was a small drop in the bolt tension. Because of this tendency a number of specimens were tested at various grips and bolt tensions in which the load on the joint was increased after each 200,000 cycles of loading. This coaxing procedure was carried up to the point where the joint started to slip or to that point at which failure of the joint occurred.

By following this coaxing procedure, it was possible in one test to increase the stress cycle to a shear of $\pm$31,900 psi before slip of the joint occurred, without failure of the bolts. In some of the other joints, as the grip was reduced, the plates started to fail or, as the bolt tension was lowered, the joints would slip. However, in no case was there a bolt failure in the fatigue tests. This result confirms the original assumption that, if there is no slip in the joints there is little likelihood of failure in the high tensile bolts.

Fatigue Strengths of Plates in Bolted Butt-type Joints

The second phase of the fatigue study of high tensile bolted structural joints is concerned with the fatigue strength of the plates. In these tests, four specific factors were studied: bolt tension, bolt diameter, length of grip, and fastener type (rivets or bolts).

All of the specimens of this group were of so-called "balanced" design; that is, the ratio of the shear stress in the bolts or rivets to the tensile stress in the plates was 0.75. This ratio is proper for balanced design of a riveted joint, but may be too low for a bolted joint. The details of the specimens for the test included in this study are presented in Figs. 7, 8 and 9. In planning this group of tests the Project Advisory Committee established a test cycle of $\pm$18,000 psi on the net section of the joint. This, it was thought, would be sufficient to produce failure. However, as may be noted in the results of the test, many of the joints withstood 2,000,000 cycles or more of load application without failure.

(a) Bolt Tension: It is difficult to interpret the results of the tests in which the bolt tension was varied because so few of the joints failed in spite of the high load cycle applied. A summary of the results of these tests is presented

in Table 10. As shown in column 4 of this table the axial bolt tensions in the 1-in. bolts were varied from 50 to 138 per cent of the specified elastic proof load. The maximum value was chosen because it is approximately the maximum axial tension which may be developed in the bolts. To obtain this high tension, it was necessary to tighten the nuts until the bolts had exceeded the yield point of the material by a considerable margin.

In those instances in which failure was obtained, the fatigue strength corresponding to failure at 2,000,000 cycles was computed from the following expression:

$$F = \frac{SN^k}{2{,}000{,}000^k} \qquad (2)$$

where,

F is the stress for failure at 2,000,000 cycles
S is the stress applied to the specimen
N is the number of cycles for failure at stress S
K is an experimental constant.

A value of K equal to 0.10, as suggested by Wilson (1), was used.

When one considers the results of the six specimens which failed in the joint, it appears that the fatigue strength does vary with the bolt tension. However, it is somewhat difficult to distinguish whether this variation in fatigue strength is a result of the variation in bolt tension or whether the larger slip which generally accompanied the lower bolt tension is the factor which caused the reduction in fatigue strength. Since a lowering of the bolt tension and an increase in the slip of the joint go hand in hand, it is very likely that the effect of these two variables cannot be separated from one another. Nevertheless, it is evident that for the higher bolt tensions the fatigue strength for failure at 2,000,000 cycles is close to $\pm$20,000 psi.

This series of tests also provides some further information concerning the fatigue strength of the high tensile bolts. The bolts in specimens A4-1, A4-2 and A4-3 did not fail in over 2,000,000 cycles of loading even though they had been elongated approximately 0.02 in. in a grip length of 1 3/4 in., an elongation which was due to considerable yielding in the bolts.

(b) Bolt Diameter: The bolt diameter studies were conducted on specimens for which the bolt diameter was varied from 5/8 to 1 in. In general, the stress cycles in this study were $\pm$18,000 psi. However, in three cases a stress cycle of $\pm$20,000 psi was used.

Of the 14 specimens reported in Table 11, only three failed in the joint. These three specimens, however, were fabricated with the 3/4 in. bolts which as was previously noted, did not quite meet the specifications (2) now recommended. In any case, it may be concluded that the fatigue strength of similar joints for failure at 2,000,000 cycles, providing that the joint does not slip and that the bolts meet the specifications, will be at least as great as 18,000 psi for a completely reversed stress cycle. Because the range of bolt sizes covers the bolt diameters most commonly used in structural practice, this conclusion is of considerable importance.

(c) Grip: The third factor considered in this study was the effect of the grip (1 3/4 to 3 3/4 in.) on the fatigue strength of joints fabricated with 1-in. high-tensile bolts and tested on a stress cycle of $\pm$18,000 psi. The results of these tests are summarized in Table 12.

In view of the three failures obtained in these tests it may be concluded that, in general, the fatigue strength of these specimens is approximately equal to $\pm$18,000 psi for failure at 2,000,000 cycles regardless of the grip.

(d) Relative Strength of Riveted and Bolted Joints: Three riveted joints of the same dimensions as the series B specimens shown at the center of Fig. 8 were tested for comparison with the tests on the series B bolted joints. A summary of the results of these tests are presented in Table 13.

The riveted joints were tested at a stress cycle of $\pm$18,000 psi, whereas two of the bolted joints were tested at the same stress cycle and three were tested at a stress cycle of $\pm$20,000 psi.

Two of the bolted joints (one at $\pm$18,000 psi and one at $\pm$20,000 psi) failed in the grip or head end of the specimen but not in the joint. All of the remaining bolted joints, however, withstood 2,000,000 to 3,000,000 cycles of load application without failure. Thus, the fatigue strength for failure at 2,000,000 cycles appears to be at least equal to 20,000 psi in full reversal for the bolted joints.

The results of the tests on riveted joints were quite different. Specimens B3R-1 and B3R-2, subjected to a stress of $\pm$18,000 psi, failed after 713,000 and 577,800 cycles, respectively. This is equivalent to a fatigue strength at 2,000,000 cycles of approximately $\pm$16,000 psi. The third riveted joint, Specimen B3R-3, was subjected to a stress of $\pm$18,000 psi also. However, after 93,000 cycles of load application it was necessary to stop the test because the joint was slipping excessively.

Based on the results of these tests it appears that these riveted joints had a fatigue strength of 16,000 psi or less, whereas a similar bolted joint using high tensile bolts with a bolt tension equal to the elastic proof load had a fatigue strength greater than 20,000 psi. This indicates that the bolted joints were about 25 % stronger in fatigue than were the similar riveted joints.

The relative slip of the riveted and bolted joints is also of interest. The bolted joints exhibited a negligible amount of slip at both the start and finish of the fatigue tests. In the case of the riveted joints a considerable slip in the joint was noted at the start of the test. This slip increased rapidly during one of the tests and decreased somewhat in the other tests.

It is of interest also to note that the results observed for Specimen B3R-3 are somewhat similar to observations which have been made in the field. In this test, as often occurs in service, the rivets worked loose under repeated loading. This is a type of loading for which high tensile strength bolts are ideally suited. The bolts, although the test results and experience indicate that they will probably not work loose, may be retightened if necessary while rivets, if they become loose, must be removed and redriven.

Fatigue Tests of Lap Joints

Lap joints are used frequently in engineering structures but have not commonly been tested in fatigue because of the many problems encountered in testing such joints. The principal difficulty results from the eccentricity of loading in lap joints. This difficulty was evident in preliminary tests conducted on single lap-joint specimens.

(a) Preliminary Tests: The results of the preliminary tests conducted on two-bolt lap-type specimens are presented in Table 14. The first of these specimens, MSA-3, was tested at a stress of $\pm$14,400 psi. Failure resulted after 126,600 cycles, a surprisingly small number of cycles.

The next step in the preliminary tests was to provide a system of sway bracing (shown in Fig. 10) for the lap joints to reduce the side sway of the specimen which resulted from the eccentricity of loading. Although this bracing eliminated most of the lateral motion of the specimen during the test,

it was difficult to interpret the practical significance of the stiffness of this braced joint. The fatigue strength for specimens tested with the sway bracing was approximately 50 o/o greater than that of the unbraced specimen.

A third approach tried in the preliminary tests consisted of placing two lap joints back to back and testing them as a double lap or a butt-type joint for which the strap plates were critical. The resulting joint was, of course, symmetrical and there was no side sway during the test. However, in this case, the stiffness of the joint was very much greater than that of the initial single lap test specimen; the specimen was subjected to more than 5,000,000 cycles of $\pm$16,000 psi without failure.

As a result of these preliminary studies a test procedure was developed in which two lap joints were tested in pairs. The details of the specimens are shown in Figs. 11, 12 and 13 and demonstrate the method of blocking which was used to vary the stiffness of the test specimens. This procedure of testing proved to be effective for tests conducted with completely reversed cycles as well as with cycles of zero to tension.

(b) Tests with Reversed Load Cycle: The three types of specimens shown in Figs. 11, 12 and 13 were tested on a reversed load cycle of $\pm$16,000 psi. The results of these tests are summarized in Table 15.

The Type C specimens, those with the least amount of restraint, had an average fatigue strength for failure at 2,000,000 cycles of approximately 11,400 psi. This value is not much greater than that obtained for the single lap joint specimen reported for the preliminary tests. The type BMS and AMS specimens, however, had fatigue strengths of 14,000 and 15,000 psi, respectively. This increase in fatigue strength indicates that the flexibility of the specimens had a pronounced effect on the fatigue strength of the joints.

Slip measurements were made in these fatigue tests; the slip per cycle was generally less than 0.002 in. at the start of the test and less than 0.001 in. at the end of the tests. As noted in column 5 of Table 15, the largest slip accumulated during the tests was 0.0021 in., a value far less than the slip required to bring the bolts into bearing. Since the tests were started with the bolts presumably in the center of the bolt holes it is evident that the entire load on the joint was carried by the friction between the plates.

(b) Tests on a Zero to Tension Load Cycle: Five lap joints of each of the three types discussed previously were subjected to a stress cycle of zero to tension. The results of these tests are presented in Table 16. The maximum tensile stress was 24,000 psi for all of these specimens except CMS-4, for which the maximum stress was only 19,750 psi.

Comparing the fatigue strengths of the specimens for failure at 2,000,000 cycles one finds that the variation in blocking or in stiffness had no significant effect on the fatigue strength of these specimens. The result is contrary to that obtained in the case of the tests conducted on a reversed load cycle where the stiffness of the specimen had a considerable effect upon the fatigue strength of the joints.

The fatigue strengths obtained in the tests of the lap joint specimens are below those obtained in the tests of the butt type joints for complete reversal, and the indications are that the relative strengths are about the same for a zero-to-tension cycle. This result is just the reverse of what was found in static tests where the lap joints were found to have a slightly greater strength than the butt type joints.

SUMMARY OF RESULTS AND CONCLUSIONS

The results of the tests reported herein may be briefly summarized as follows:

Static Tests

1. The bolt tension appears to have very little effect on the ultimate strength of bolted joints. However, the load-slip characteristics of the joints are greatly affected by the axial tension in the bolts. In general, when the bolt tension is at least 85 percent of the elastic proof load, in joints where rivets are replaced by bolts, slip does not occur until stresses in the plate are reached about equal to or slightly greater than normal working stresses.
2. Tests of two-bolt and three-bolt lap joints and two-bolt butt joints indicate that the type of joint has little effect on the ultimate strength.
3. Based on the ultimate tensile strengths obtained in the static tests it appears that the permissible shearing stress might be increased to a value approximately 1.25 times the permissible tensile stress in order to obtain a balanced design. If this is done, however, it will be necessary also to increase the minimum safe end distance now permitted for such joints. Furthermore, slip may occur at loads below normal working loads unless special efforts are taken to prevent slip.

Fatigue Tests

1. In no case was there a fatigue failure of the high tensile bolts in the joints providing there was no slippage of the joints during the application of load. This is true in spite of the fact that the joints were designed to subject the bolts to unusually severe loading conditions.
2. It is essential that the bolts be torqued up tight, in accordance with the present specifications (2), to obtain the greatest benefits from the use of high tensile bolts.
3. Tests of duplicate specimens fabricated with rivets and bolts demonstrate that the fatigue strength of bolted joints, properly assembled, is approximately 25 per cent greater than that of similar riveted joints.

These laboratory tests indicate extremely promising results for high tensile bolted structural joints under both static and fatigue type loadings.

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These laboratory studies were conducted by D. T. Wright, M. A. Cayci, F. W. Schutz, Jr. and H. L. Cox, Research Assistants in Civil Engineering, in the Structural Research Laboratory.

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TABLE 1

MECHANICAL PROPERTIES OF BOLT MATERIAL

(Tests of 0.505-in. diam. Specimens)

Bolt Diameter in.	Specimen Number	Yield Strength, psi+	Tensile Strength, psi	Elongation in 2 in., per cent	Reduction in Area, per cent
3/4	C1-1	84,500	114,500	22	61
	C1-2	82,500	111,500	24	65
	C1-3	85,000	113,800	23	62
	Average	84,000	113,200	23	63
7/8	C2-1	97,200	123,300	23	57
	C2-2	75,900	110,600	22	61
	C2-3	95,000	122,300	22	58
	Average	89,400	118,700	22	59
1	C3-1	100,900	126,800	21	58
	C3-2	105,300	129,300	19	53
	C3-3	97,900	125,300	21	56
	Average	101,400	127,100	20	56
ASTM* Minimum Requirements					
7/8 and 1		78,000		14	35

+ Yield Strength by Drop-of-the-Beam Method.

* ASTM Specification A325-49T does not give requirements for machined test specimens from bolts smaller than 7/8-in. diameter.

TABLE 2

ULTIMATE STRENGTH OF TEST BOLTS

Bolt Diameter, in.		Number of Tests	Ultimate Load, lb.	Tensile Strength,* psi
3/4	Averaged Test Result	7	39,900	119,500
	ASTM Requirements+		40,000	120,000
7/8	Averaged Test Result	4	66,900	145,000
	ASTM Requirements+		50,700	110,000
1	Averaged Test Result	10	79,200	131,000
	ASTM Requirements+		66,500	110,000

* Based on mean area of threaded section.

\+ ASTM Specification A325-49T.

TABLE 3

SUMMARY OF VALUES OF TORQUE COEFFICIENT, K

Grip in.	Specimen Number	Bolt Diameter, in. 3/4	7/8	1
3-3/4	1	0.242	0.210	0.207
	2	0.292	0.196	0.247
	3	0.220	0.231	0.207
	4	0.181	0.206	0.243
2-1/4	5	0.207	0.213	0.208
	6	0.226	0.211	0.224
	7	0.244	0.222	0.208
	8	0.247	0.219	0.196
Averages		0.232	0.213	0.217

Grand Average of All Tests = 0.221

Probable error = ± 0.016

TABLE 4

DESCRIPTION OF SPECIMENS FOR STATIC TESTS

Series No. (1)	Joint Type (2)	Plate Thickness t, in. (3)	Plate Thickness t_1, in. (4)	End Distance e, in. (5)	Tension-Shear Ratio (6)
S7	Lap	3/8	---	2	0.75
S8	Lap	1/2	---	1-1/2	1.00
S9	Lap	5/8	---	1-1/4	1.25
S10	Lap	5/8	---	1-1/2	1.25
S11	Lap	5/8	---	1-3/4	1.25
S12	Lap	3/8	---	2	0.75
S13	Lap	1/2	---	1-1/2	1.00
S14	Lap	5/8	---	1	1.25
S15	Butt	3/8	7/8	2	0.75
S16	Butt	1/2	1-1/4	1-1/2	1.00
S17	Butt	5/8	1-1/2	1-1/2	1.25

TABLE 5

RESULTS OF STATIC TESTS OF TWO-BOLT LAP-TYPE JOINTS

Spec. No. (1)	Bolt Tension lb. (2)	Contact Surfaces* (3)	Maximum Load, lb. (4)	Type of Failure+ (5)	Stresses at Maximum Load: Tension psi (6)	Stresses at Maximum Load: Shear psi (7)
S7-1	0	M.S.	58,200	T	66,100	48,400
S7-2	35,000	M.S.	57,500	T	65,800	47,700
S7-4	0	Lq.	58,200	T	65,400	48,400
S7-5	35,000	Lq.	58,700	T	65,600	48,800
		Average	58,150		65,720	48,320
S8-1	0	M.S.	72,800	T	61,800	60,500
S8-2	35,000	M.S.	73,400	T	62,200	61,000
S8-4	0	Lq.	74,000	T	62,800	61,500
S8-5	35,000	Lq.	75,300	T	63,800	62,500
		Average	73,870		62,650	61,370
S9-1	0	M.S.	83,600	ET	55,800	69,500
S9-2	35,000	M.S	84,700	ET	55,600	70,400
S9-4	0	Lq.	83,700	ET	55,500	69,600
S9-5	35,000	Lq.	81,200	ET	54,100	76,400
		Average	83,300		55,250	71,470
S10-1	0	M.S.	101,000	S	67,200	84,000
S10-2	35,000	M.S.	103,500	S	68,800	86,000
S10-3	0	Lq.	102,800	S	68,100	85,100
S10-4	35,000	Lq.	102,600	S	67,900	84,900
		Average	102,470		68,000	85,000
S11-1	0	M.S.	102,400	S	67,800	84,800
S11-2	35,000	M.S.	102,000	T	67,600	84,500
S11-3	0	Lq.	98,400	S	65,200	81,500
S11-4	35,000	Lq.	102,300	T	67,800	84,800
		Average	101,270		67,350	83,900

* M. S. indicates dry mill-scale surfaces.
Lq. indicates lacquered surfaces.

\+ S indicates a shear (fastener) failure.
T indicates a tension (plate) failure.
ET indicates a tearing out at the ends of the plates.

TABLE 6

RESULTS OF STATIC TESTS OF THREE-BOLT LAP-TYPE JOINTS

Spec. No. (1)	Bolt Tension, lb. (2)	Contact Surfaces* (3)	Maximum Load, lb. (4)	Type of Failure+ (5)	Stresses at Maximum Load Tension psi (6)	Shear psi (7)
S12-1	0	M.S.	85,300	T	63,100	47,300
S12-2	35,000	M.S.	85,900	T	64,200	47,500
S12-4	0	Lq.	85,100	T	63,600	47,100
S12-5	35,000	Lq.	85,800	T	63,900	47,300
		Average	85,520		63,700	47,300
S13-1	0	M.S.	118,600	T	66,400	65,700
S13-2	35,000	M.S.	118,300	T	65,800	65,100
S13-4	0	Lq.	118,200	T	66,400	65,100
S13-5	35,000	Lq.	120,800	T	67,000	67,000
		Average	118,970		66,400	65,720
S14-1	0	M.S.	149,500	T	67,200	82,700
S14-2	35,000	M.S.	144,100	T	64,600	79,500
S14-4	0	Lq.	152,400	T	68,300	84,000
S14-5	35,000	Lq.	152,200	T	68,100	84,400
		Average	149,550		67,050	82,650

* M.S. indicates dry mill-scale surfaces.
Lq. indicates lacquered surfaces.

\+ T indicates a tension (plate) failure.

TABLE 7

RESULTS OF STATIC TESTS OF TWO-BOLT BUTT-TYPE JOINTS

Spec. No. (1)	Bolt Tension, lb. (2)	Contact Surfaces* (3)	Maximum Load, lb. (4)	Type of Failure+ (5)	Stresses at Maximum Load: Tension psi (6)	Stresses at Maximum Load: Shear psi (7)
S15-1	0	M.S.	117,800	T	65,100	48,800
S15-2	35,000	M.S.	120,300	T	66,000	50,200
S15-3	0	Lq.	116,600	T	64,300	48,200
S15-4	35,000	Lq.	118,400	T	65,200	48,900
		Average	118,270		65,150	49,020
S16-1	0	M.S.	154,700	T	65,100	64,400
S16-2	35,000	M.S.	155,900	T	65,500	64,800
S16-3	0	Lq.	151,800	S	63,800	63,200
S16-4	35,000	Lq.	155,000	T	65,100	64,400
		Average	154,350		64,870	64,200
S17-1	0	M.S.	179,500	S	59,700	74,600
S17-2	35,000	M.S.	197,000	S	65,400	81,800
S17-3	0	Lq.	194,700	S	64,800	81,000
S17-4	35,000	Lq.	198,900	S	66,300	82,200
		Average	192,520		64,050	79,900

* M.S. indicates dry mill-scale surfaces.
Lq. indicates lacquered surfaces.

\+ S indicates a shear (fastener) failure.
T indicates a tension (plate) failure.

TABLE 8

RESULTS OF STATIC TESTS OF RIVETED JOINTS

Spec. No.	Contact Surfaces*	Maximum Load, lb.	Type of Failure+	Stresses at Maximum Load	
				Tension psi	Shear psi
(1)	(2)	(3)	(4)	(5)	(6)
S7-3	M.S.	57,800	T	65,000	48,000
S7-6	Lq.	58,400	T	65,600	48,700
S8-3	M.S.	65,200	S	55,600	54,200
S8-6	Lq.	68,300	S	57,800	56,800
S9-3	M.S.	65,600	S	43,400	54,000
S9-6	Lq.	69,000	S	45,900	57,300
S12-3	M.S.	82,500	T	61,200	45,900
S12-6	Lq.	84,800	T	62,900	47,200
S13-3	M.S.	103,400	S	57,200	57,200
S13-6	Lq.	108,700	S	60,600	60,000
S14-3	M.S.	103,100	S	46,100	57,200
S14-6	Lq.	106,500	S	47,600	59,000

* M.S. indicates dry mill-scale surfaces.
Lq. indicates lacquered surfaces.

+ S indicates a shear (fastener) failure.
T indicates a tension (plate) failure.

TABLE 9

RESULTS OF TESTS MADE TO DETERMINE THE FATIGUE STRENGTH
OF THE BOLTS IN BUTT-TYPE JOINTS

No bolt failures observed.
Plates which failed or slipped indicated by notes (1) or (2)

Spec. No.	Grip, in.	Bolt Tension lb/bolt 1-in. Bolts	Fatigue Test		
			Stress Cycle, Complete Reversal		Cycles in 1000's
			Max. Tension and Compression, psi	Max. Shear psi	
X-3	4	45,500	6,250	19,700	4208.9
X-5	4	65,000	7,230	27,000	3654.2
ASD1-1	4	21,500	3,140	8,680	886.6
			3,260	9,000	2203.4
ASD3-1	4	55,500	7,160	19,750	207.7
			8,680	24,000	215.9
			10,200	28,200	198.9
ASD2-A	4	41,500	5,850	16,100	200.9
			7,100	19,600	200.0
			7,960	21,900	200.0
			8,350	23,000	199.8
ASD3-A	4	53,500	4,610	12,700	200.6
			6,920	19,100	200.0
			8,070	22,300	206.6
			9,230	25,300	200.0
			10,400	28,700	207.0
			11,500	31,900	200.0
DSD2-A	2-1/2	35,000	5,210	9,000	200.2
			6,210	10,700	240.8
DSD3-A	2-1/2	50,000	9,240	15,900	204.0
			11,100	19,100	200.1
			12,950	22,300	210.6
			14,800	25,500	206.6
			16,650	28,700	8.6(1)
CSD1-A	1-5/8	19,000	4,930	5,100	199.6
			6,160	6,370	200.1
			7,200	7,650	200.1(1)
CSD2-A	1-5/8	34,500	9,550	9,880	200.5
			11,580	12,000	200.0
			12,920	13,350	160.7(2)
CSD3-A	1-5/8	41,000	12,320	12,750	200.0
			15,400	15,900	200.1
			18,500	19,100	33.7(2)
FSD2-1	2	35,000	17,250	13,400	2194.9
			20,600	15,600	278.8(2)
FSD3-1	2	50,000	20,600	15,800	1656.4(2)

(1) Slipped.
(2) Plate failed.

TABLE 10

EFFECT OF BOLT TENSION ON FATIGUE STRENGTH
OF BOLTED BUTT-TYPE JOINTS

		Bolt Tension 1-in. bolts		Fatigue Test		
Spec. No. (1)	Grip in. (2)	lb./Bolt (3)	per cent of Spec. E.P.L. (4)	Stress Cycle psi (5)	Cycles in 1000's (6)	Remarks (7)
A1-1	1-3/4	23,600	50	±18,000	924.6	Failed, $F_{2,000,000}$=16,700
A1-2	1-3/4	23,600	50	±18,000	1,499.7	Failed, $F_{2,000,000}$=17,500
A1-3	1-3/4	23,600	50	±18,000	1,469.8	Failed, $F_{2,000,000}$=17,450
A2-1	1-3/4	35,400	75	±18,000	1,952.4	Failed, $F_{2,000,000}$=17,900
A2-2	1-3/4	35,400	75	±18,000	1,406.4	Failed, $F_{2,000,000}$=17,400
A2-3	1-3/4	35,400	75	±18,000	2,067.1	Did not fail.
A3-1	1-3/4	47,200	100	±18,000	2,046.1	Did not fail.
A3-2	1-3/4	47,200	100	±18,000	2,135.8	Did not fail.
A3-3	1-3/4	47,200	100	±18,000	2,205.5	Did not fail.
FSD3-1	2	50,000	106	±20,600	1,656.4	Failed, $F_{2,000,000}$=20,200
A4-1	1-3/4	65,000	138	±18,000	2,024.5	Did not fail.
A4-2	1-3/4	65,000	138	±18,000	2,036.1	Did not fail.
A4-3	1-3/4	65,000	138	±18,000	2,029.9	Did not fail.

TABLE 11

EFFECT OF BOLT DIAMETER ON FATIGUE STRENGTH
OF BOLTED BUTT-TYPE JOINTS

		Bolt Tension		Fatigue Test		
Spec. No. (1)	Bolt Diam. in. (2)	Lb./Bolt (3)	per cent of Spec. E.P.L. (4)	Stress Cycle psi (5)	Cycles in 1000's (6)	Remarks (7)
A3-1	1	47,200	100	±18,000	2,046.1	Did not fail
A3-2	1	47,200	100	±18,000	2,135.8	Did not fail
A3-3	1	47,200	100	±18,000	2,205.5	Did not fail
B3-1	7/8	36,000	100	±20,000	2,126.7	Did not fail
B3-2	7/8	36,000	100	±20,000	434.8	Failed in head
B3-3	7/8	36,000	100	±18,000	1,960.3	Failed in head
B3-4	7/8	36,000	100	±20,000	2,068.3	Did not fail
B3-5	7/8	36,000	100	±18,000	3,883.6	Did not fail
C3-1	3/4	23,700	83.5	±18,000	517.4	Failed, $F_{2,000,000}$=15,700*
C3-2	3/4	25,100	88.5	±18,000	2,108.8	Failed, $F_{2,000,000}$=18,100
C3-3	3/4	25,500	90	±18,000	1,998.2	Failed, $F_{2,000,000}$=18,000
D3-1	5/8	19,200	100	±18,000	2,083.5	Did not fail
D3-2	5/8	19,200	100	±18,000	2,100.0	Did not fail
D3-3	5/8	19,200	100	±18,000	5,538.5	Failed in plate

* Specimen C3-1 slipped excessively. After failure it was found that there was some oil between the plates.

TABLE 12

EFFECT OF GRIP ON FATIGUE STRENGTH
OF BOLTED BUTT-TYPE JOINTS

Spec. No. (1)	Bolt* Tension lb./Bolts 1-in. Bolts (2)	Plate Thickness Inside in. (3)	Plate Thickness Outside in. (4)	Grip in. (5)	Fatigue Test Stress Cycle psi (6)	Fatigue Test Cycles in 1000's (7)
A3-1	47,200	3/4	1/2	1-3/4	±18,000	2046.1
A3-2	47,200	3/4	1/2	1-3/4	±18,000	2135.8
A3-3	47,200	3/4	1/2	1-3/4	±18,000	2205.5
AG1-1	47,200	3/4	3/4	2-1/4	±18,000	2236.1**
AG1-2	47,200	3/4	3/4	2-1/4	±18,000	3090.1
AG1-3	47,200	3/4	3/4	2-1/4	±18,000	2000.5
AG2-1	47,200	3/4	1	2-3/4	±18,000	2038.3
AG2-2	47,200	3/4	1	2-3/4	±18,000	1619.1**
AG2-3	47,200	3/4	1	2-3/4	±18,000	2018.5
AG3-1	47,200	3/4	1-1/2	3-3/4	±18,000	2054.4
AG3-2	47,200	3/4	1-1/2	3-3/4	±18,000	2065.5
AG3-3	42,500+	3/4	1-1/2	3-3/4	±18,000	817.1**

* Bolt tension is equal to 100 percent of specified elastic proof load.

** Only specimens AG1-1, AG2-2 and AG3-3 failed. Others did not fail.

\+ Bolt tension was accidently reduced.

TABLE 13

RELATIVE FATIGUE STRENGTH OF BOLTED AND RIVETED BUTT-TYPE JOINTS

Spec. No.	Fastener	Bolt Tension, Lb./Bolt	Fatigue Test: Stress Cycle psi	Fatigue Test: Cycles in 1000's	Slip per Cycle in 0.001 in.: Start	Slip per Cycle in 0.001 in.: Finish	Remarks
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
B3-1	Bolts	36,000	±20,000	2,126.7	0.3	0.2	Did not fail
B3-2	Bolts	36,000	±20,000	434.8	0.4	0.1	Failed in head
B3-3	Bolts	36,000	±18,000	1,960.3	0.0	0.1	Failed in head
B3-4	Bolts	36,000	±20,000	2,068.3	0.2	0.3	Did not fail
B3-5	Bolts	36,000	±18,000	3,883.6	0.2	0.2	Did not fail
B3R-1	Rivets	---	±18,000	713.5	8.5	4.0	Failed, $F_{2,000,000}$ = 16,000
B3R-2	Rivets	---	±18,000	577.8	3.6	3.3	Failed, $F_{2,000,000}$ = 15,900
B3R-3	Rivets	---	±18,000	93.2	15.0	156	Test stopped, excessive slip

Note: All joints had a shear ratio of 0.72 and a grip of 1-3/4 in.
All fasteners, bolts and rivets, were 7/8 in. nominal diameter.

TABLE 14

RESULTS OF PRELIMINARY FATIGUE TESTS OF LAP-TYPE JOINTS

Spec. No.	Type of Joint	Bolt Tension Kips/Bolt	Stress Cycle psi	Cycles to Failure 1000's
(1)	(2)	(3)	(4)	(5)
MSA-3	Single Lap, No Bracing	35.0	±14,400	126.6
48-12-1	Single Lap with Sway Bracing	35.0	±16,000	1,376.1
49-1-1	Single Lap with Sway Bracing	35.0	±16,000	1,310.0
49-1-2	Single Lap with Sway Bracing	35.0	0 to +24,000	3,078.0
48-12-2	Double-Strap Butt Joint	35.0	±16,000	5,567.0*

*Specimen did not fail.

Note: All joints had shear ratios of unity;
all bolts were 7/8 in. diameter.

TABLE 15

FATIGUE STRENGTH OF BOLTED LAP-TYPE JOINTS
FOR A COMPLETELY REVERSED LOAD CYCLE

Spec. No. (1)	Stress Cycle, psi (2)	Cycles for Failure, 1000's (3)	$F_{2,000,000}$ (4)	Total Cumulative Slip, in. (5)
AMS-9	±16,000	948.3	14,800	-0.0007
AMS-12	±16,000	948.3	14,800	+0.0015
AMS-13	±16,000	983.7	14,900	+0.0012
AMS-11	±16,000	1,406.6	15,400	+0.0017
AMS-14	±16,000	1,329.3	15,300	+0.0020
Average			15,000	+0.0011
BMS-11	±16,000	524.4	14,000	+0.0008
BMS-9	±16,000	524.4	14,000	+0.0005
BMS-14	±16,000	407.1	13,600	-0.0021
BMS-16	±16,000	447.6	13,800	-0.0014
BMS-10	±16,000	764.8	14,500	-0.0005
Average			14,000	-0.0012
CMS-10	±16,000	137.5	12,200	---
CMS-12	±16,000	137.5	12,200	---
CMS-13	±16,000	4.3	8,600	---
CMS-9	±16,000	152.9	12,400	---
CMS-16	±16,000	89.2	11,700	---
Average			11,400	---

Note: All joints had a tension-shear ratio of unity; all bolts were 7/8 in. diameter.

TABLE 16

FATIGUE STRENGTH OF BOLTED LAP-TYPE JOINTS
FOR A ZERO-TO-TENSION LOAD CYCLE

Spec. No. (1)	Stress Cycle: Zero to Tension, psi (2)	Cycles for Failure, 1000's (3)	$F_{2,000,000}$ (4)	Total Cumulative Slip, in. (5)
AMS-4	+24,000	866.5	22,100	0.0040
AMS-7	+24,000	823.6	22,100	0.0064
AMS-6	+24,000	1,095.4	22,600	0.0131
AMS-5	+24,000	1,095.4	22,600	0.0131
AMS-2	+24,000	1,143.8	22,700	0.0037
Average			22,400	0.0081
BMS-1	+24,000	1,660.3	23,600	0.0085
BMS-7	+24,000	785.9	21,900	0.0019
BMS-6	+24,000	785.9	21,900	0.0066
BMS-3	+24,000	1,687.7	23,600	0.0092
BMS-5	+24,000	2,005.0	24,000	---
Average			23,000	0.0065
CMS-4	+19,750	2,708.2	20,400	0.0036
CMS-8	+24,000	1,046.3	22,500	0.0006
CMS-5	+24,000	1,183.4	22,800	---
CMS-6	+24,000	1,090.5	22,600	0.0004
CMS-18	+24,000	495.1	20,900	---
Average			21,800	0.0015

Note: All joints had a shear-tension ratio of unity; all bolts were 7/8 in. diameter.

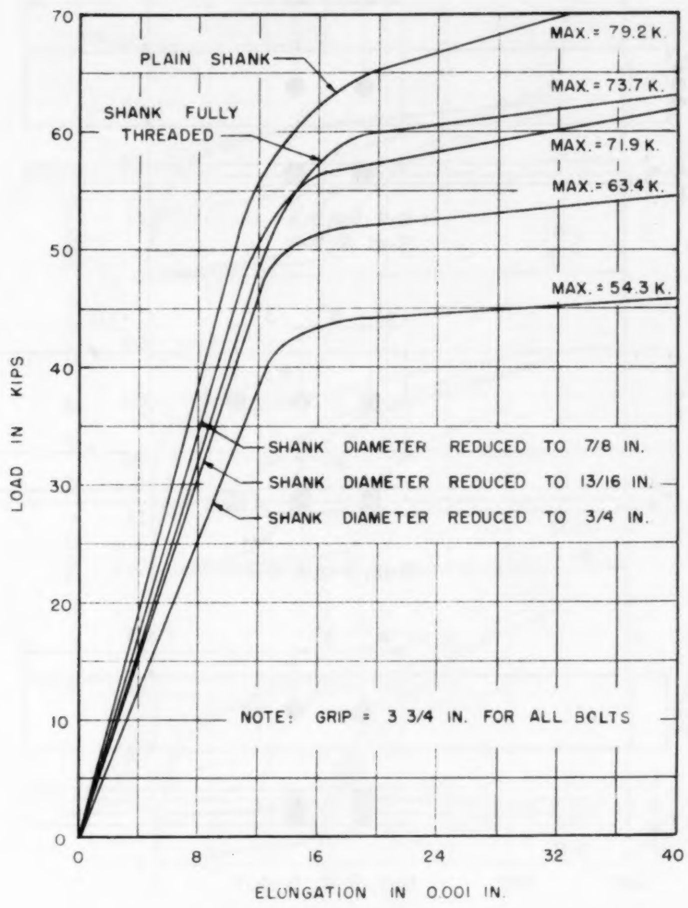
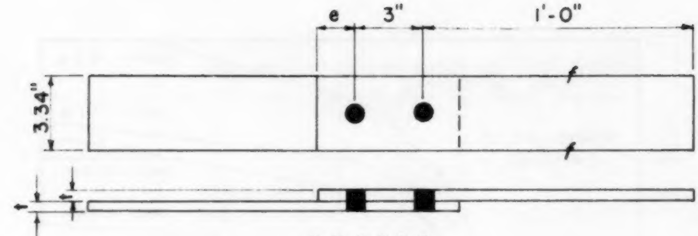
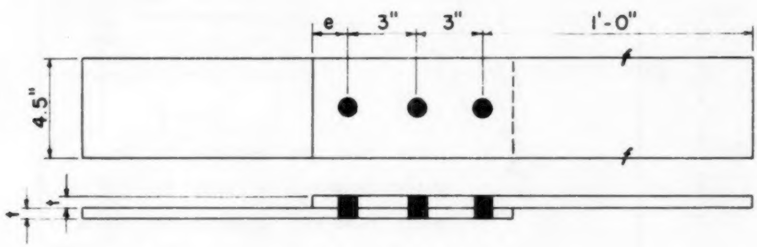


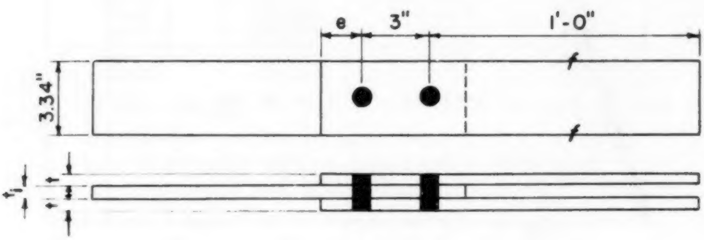
FIG. 1 LOAD - ELONGATION CURVES FOR 1 IN. BOLTS WITH VARIOUS SHANK CONDITIONS



S-7, S-8, S-9
S-10 & S-11



S-12, S-13, & S-14



S-15, S-16, & S-17

FIG. 2 DETAILS OF THE SPECIMENS FOR STATIC TESTS

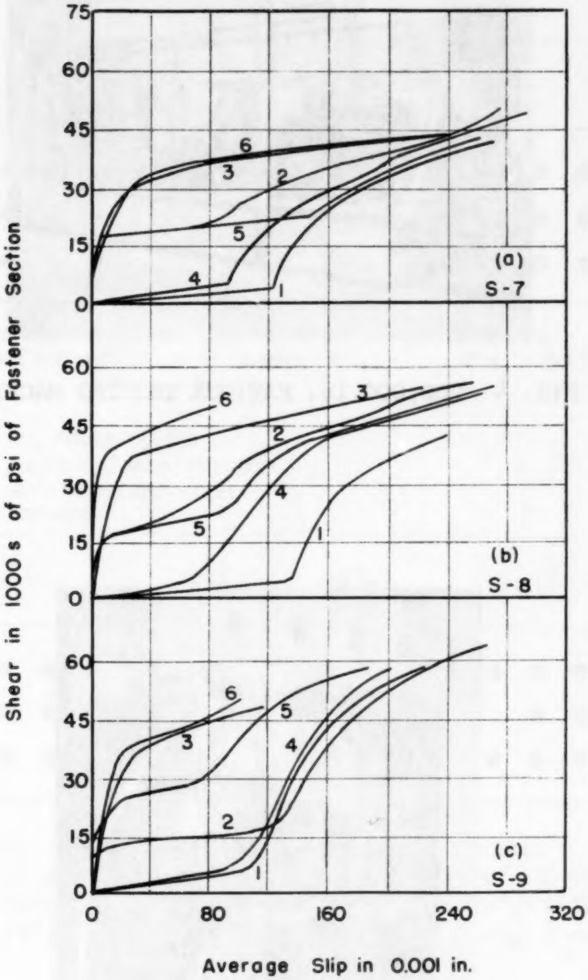


FIG. 3 LOAD-SLIP RELATION FOR JOINTS S-7 TO S-9

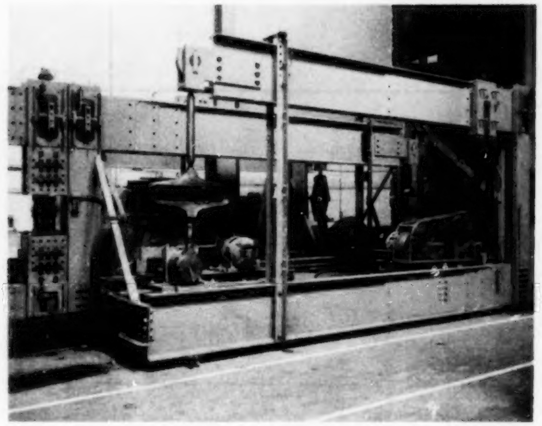


FIG. 4 200,000 lb. FATIGUE TESTING MACHINE

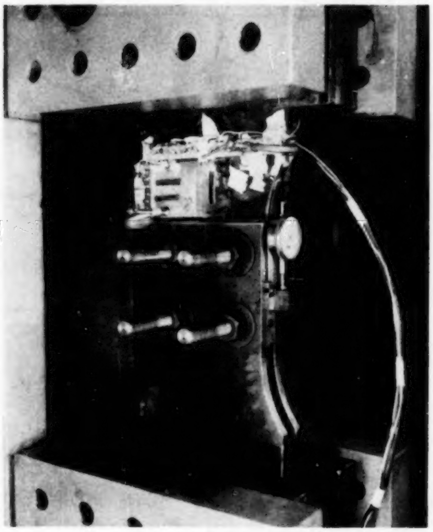


FIG. 5 FATIGUE TEST SPECIMEN B3-1 IN TESTING MACHINE

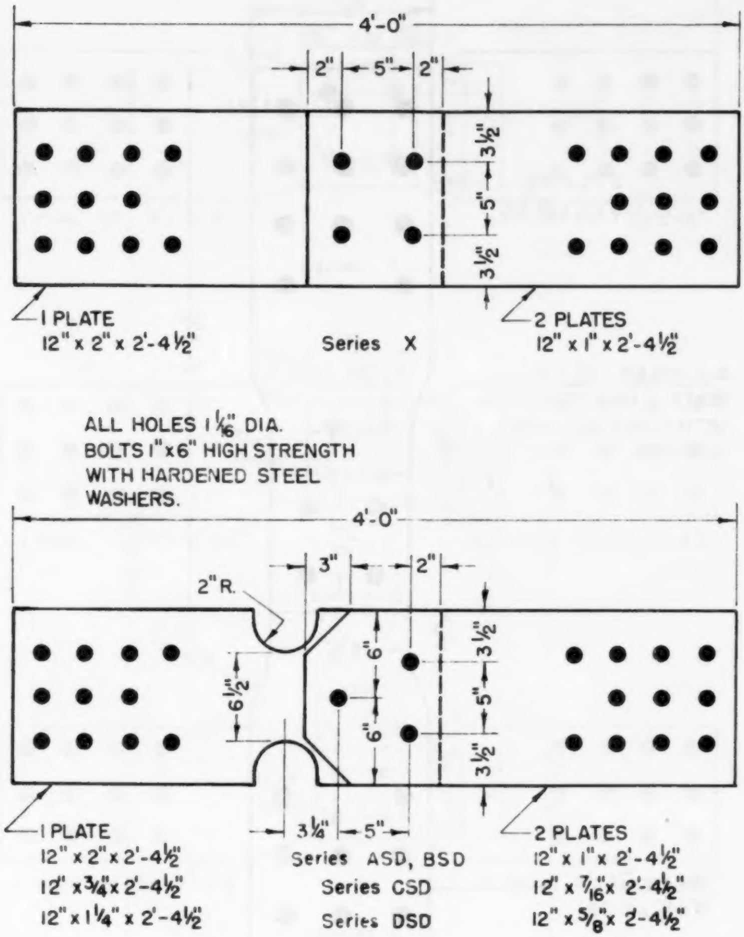


FIG. 6 SPECIMENS FOR FATIGUE TESTS OF BOLTED STRUCTURAL JOINTS, SERIES X, ASD, BSD, CSD, AND DSD

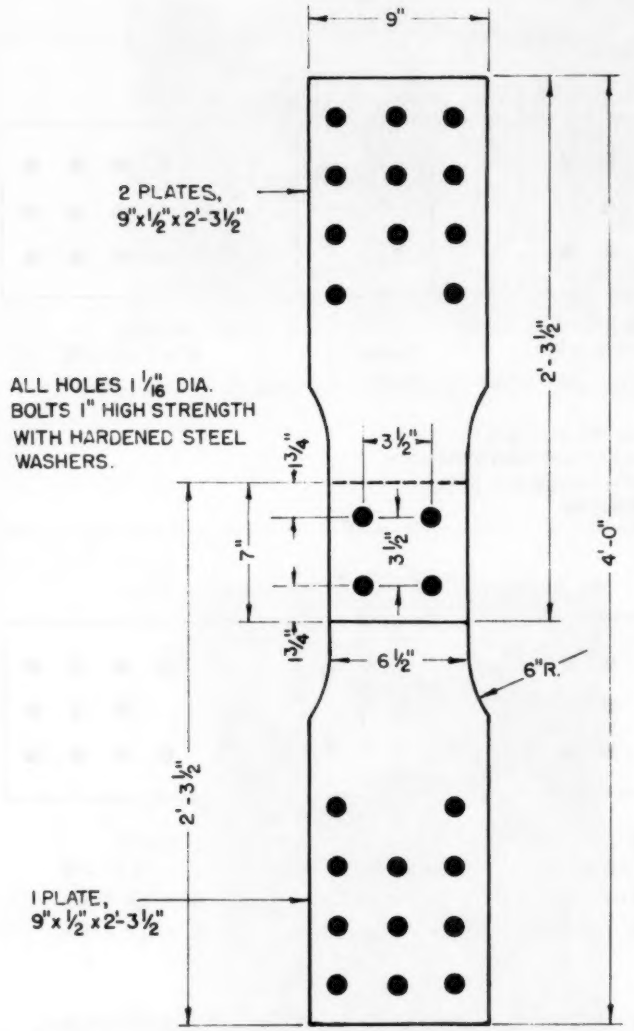


FIG.7 BOLTED FATIGUE TEST SPECIMENS OF BALANCED DESIGN, SERIES F.

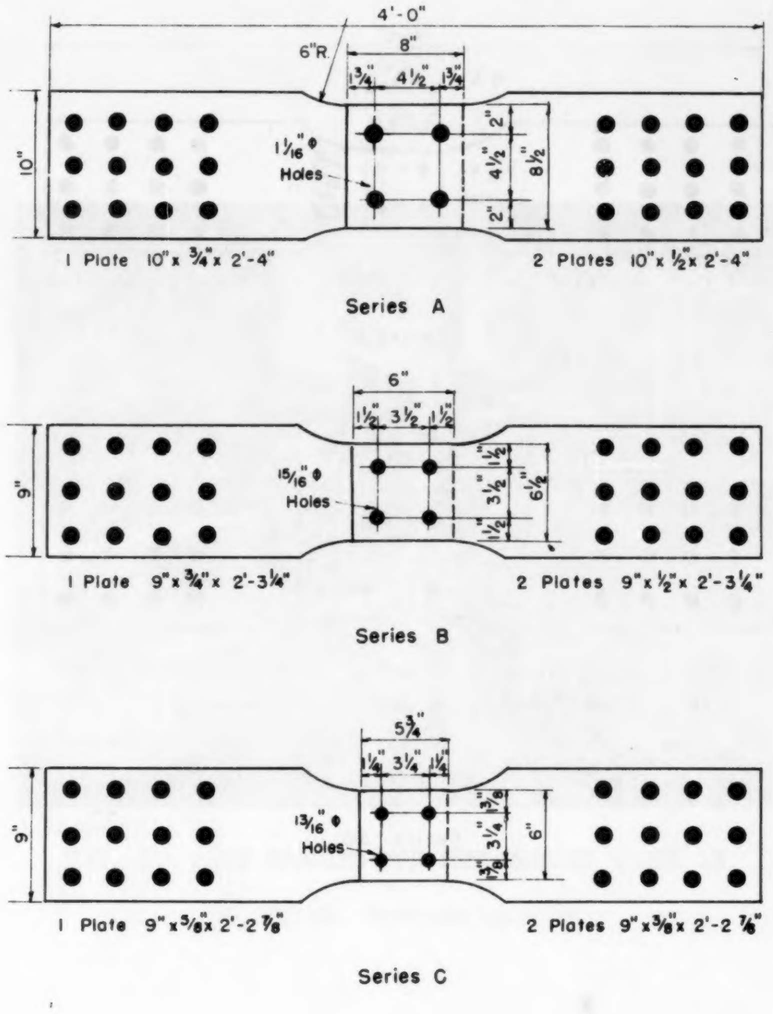
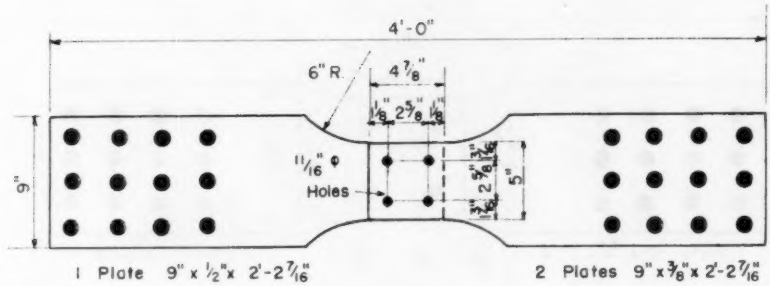
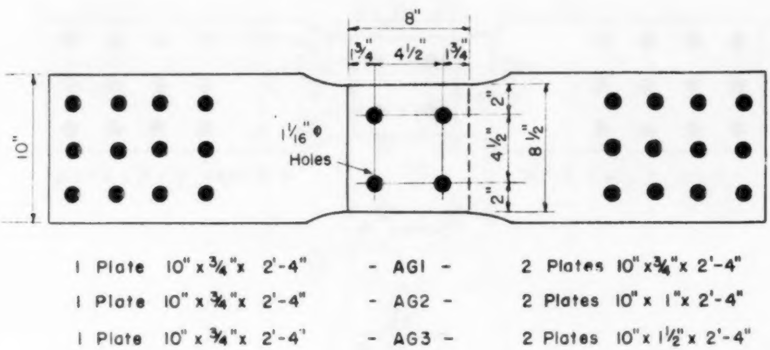


FIG. 8 BOLTED FATIGUE TEST SPECIMENS, SERIES A, B, AND C



Series D



Series AG

FIG. 9 BOLTED FATIGUE TEST SPECIMENS, SERIES D AND AG

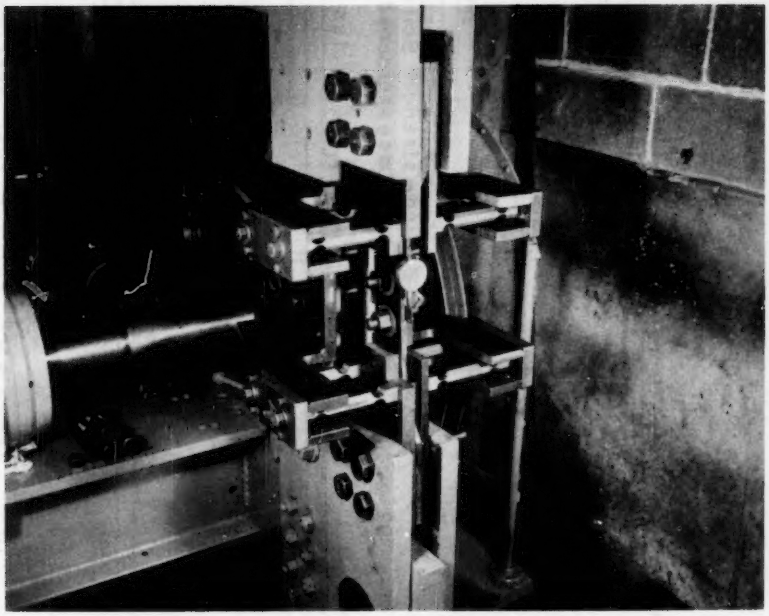


FIG. 10 SWAY BRACING FOR PRELIMINARY TESTS IN

50,000 LB. FATIGUE MACHINE

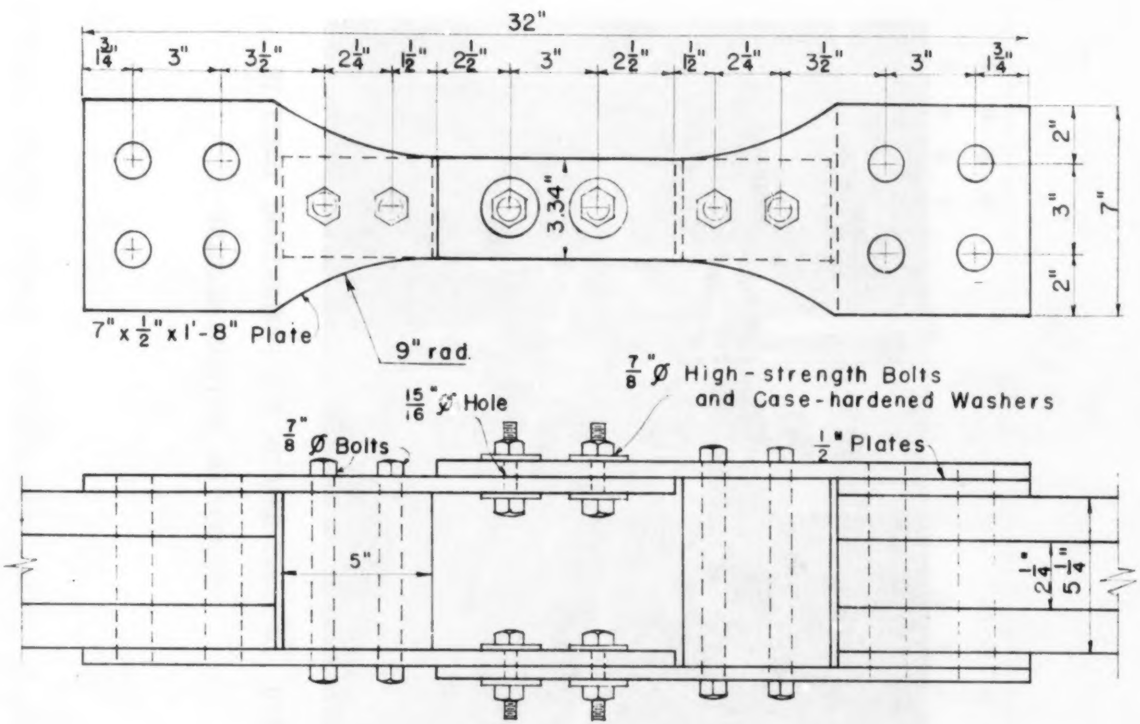


Fig. 11 Type AMS Fatigue Test Specimen

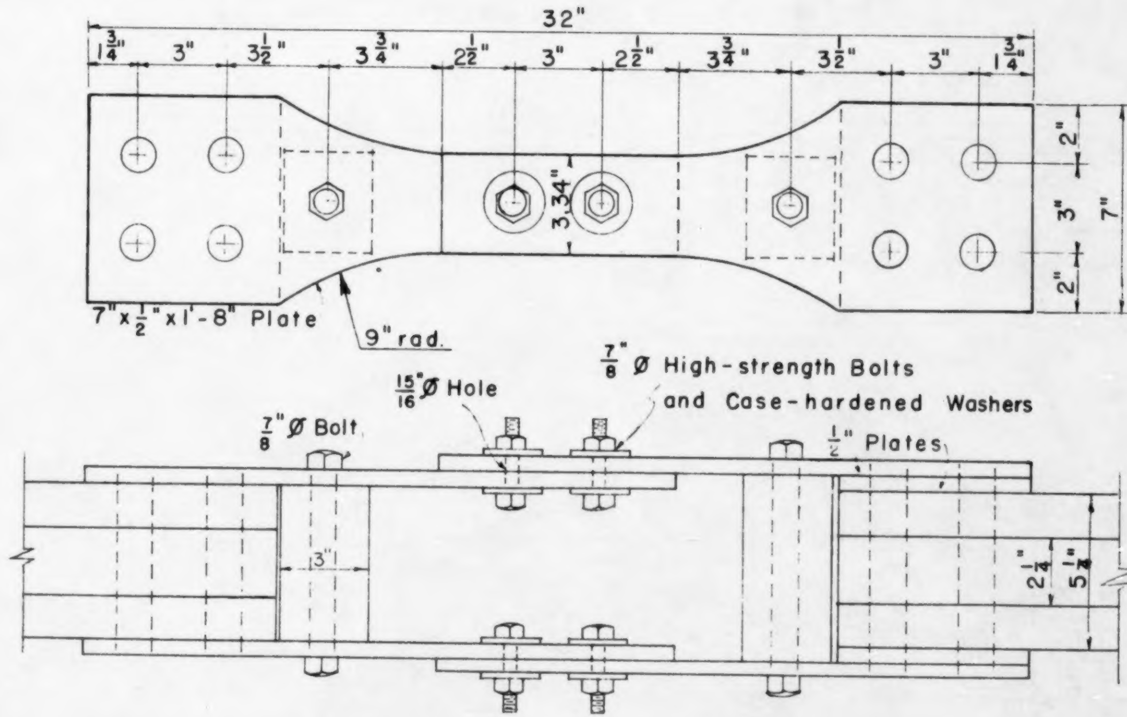


Fig. 12 Type BMS Fatigue Test Specimen

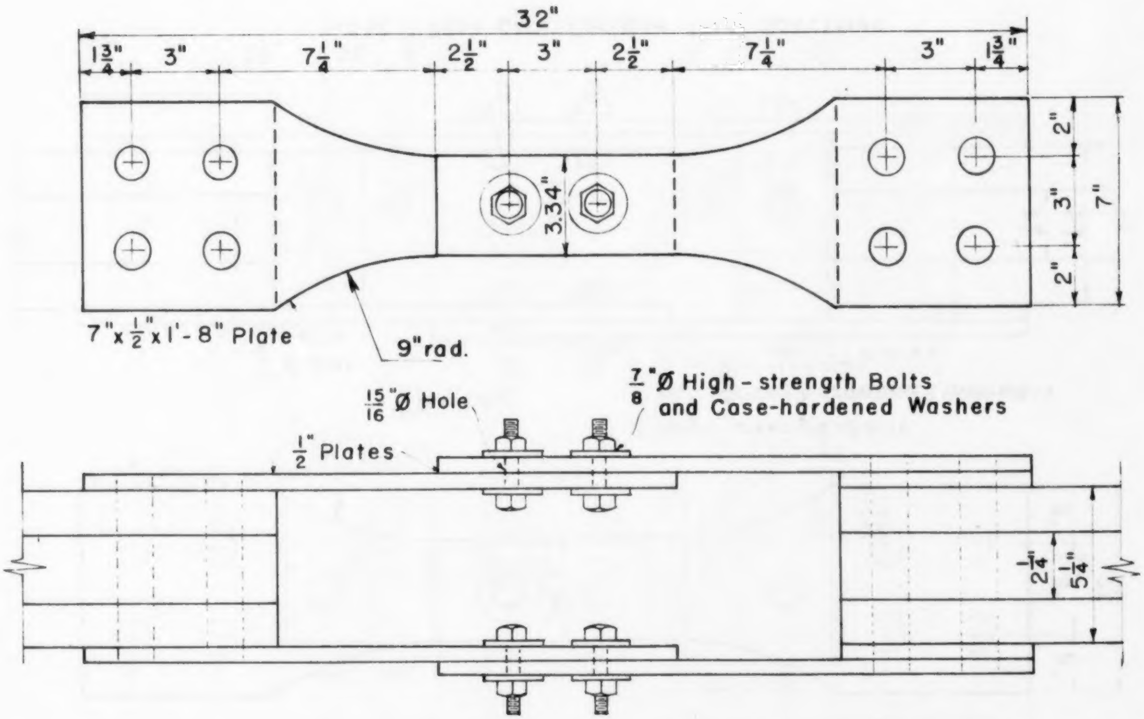


Fig. 13 Type CMS Fatigue Test Specimen